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Human Tolerance To Acceleration Loads Generated In High-Performance Helicopters

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Running Head: Helicopter G-Tolerance

ABSTRACT

Background: The risk to helicopter aircrew of acceleration stress was assessed by investigating the human physiologic response to transitions from –1 Gz (push) to +4.5 Gz (pull) loads. ***Methods:*** 9 volunteers participated in a study conducted at the Veridian Operations Centrifuge Facility in Warminster, PA. A one hr mission scenario consisting of nine helicopter maneuvers, based on in-flight G measurements (push-pull mission, PPM), simulated both current (CM: -0.2 to +3.5 Gz) and projected future platform capabilities (FM: -1 Gz to +4.5 Gz). Additional scenarios were run in which push transitions were limited to +1 Gz (GM). Measurements included blood pressure, heart rate (HR), loss of vision, and subjective fatigue. ***Results:*** Visual decrements were minimal during CM while muscular tensing was required to avoid blackout during FM. Light loss typically occurred during the transition from -Gz to +Gz. Within the scope of these tests, subjects tolerated the range of Gz-stresses associated with current USN rotary wing platforms. When subjected to FM G-loads (typical of current USA platforms), cardiovascular stress significantly increased, Gz tolerance dropped as much as 1.2 G, and HR increased as much as 67 bpm. Cardiovascular changes were significantly greater during FM PPM relative to GM. Four subjects reported Almost-Loss of Consciousness symptoms during FM. ***Conclusions:*** While G-stress experienced by aircrew generated by current helicopters does not appear to present a high risk, G awareness training is recommended to reduce risks to aircrew exposed to G-loads generated by more aggressive helicopters. Future studies are required to determine the impact of longer mission times and dehydration.

Keywords: Helicopters, G-tolerance, cardiovascular, A-LOC, flight simulation

INTRODUCTION

Current high-performance helicopters have the capability to generate and sustain acceleration forces as high as +4 Gz. Some two-seat platforms also have the capability to generate G-forces below 1 g. For example, the 1994-1995 edition of Jane's All the World's Aircraft lists the U.S. Navy/U.S. Marine Corps AH-1W Super Cobra (range: +0.5 to +3.5 Gz), the U.S. Army AH-64D Longbow Apache (range: -0.5 to +3.5 Gz), and the U.S. Army RAH-66 Comanche (range: -1.0 to +3.5 Gz). Table I lists the operational guideline for acceleration limits (not airframe limits) of several military helicopters.

(TABLE I HERE)

While these G-levels are relatively low when compared to tactical aircraft and helicopters cannot sustain G-loads for long periods of time (airspeed and rotor RPM bleed off), the nature of rotary wing missions presents a potential danger. Helicopter missions are often flown at low altitudes, e.g., 100 ft AGL. At that height, G-induced symptoms which may lead to confusion, diminished visual field, or reduced situational or spatial awareness can have catastrophic consequences.

A common problem in helicopter operations is heat stress associated with wearing protective garments. +Gz-tolerance decreases by 8% when subjects are 1% dehydrated and by 16% when they are 3% dehydrated (1). Allan and Crossley (2) found that relaxed (no anti-G suit or anti-G straining) G-tolerance was reduced by +0.9 Gz when mean aural temperature increased by 1.3°C. Under these conditions, even the relatively low +Gz-loads generated in rotary flight may present a safety hazard.

This hazard may be compounded during maneuvers which include transitions from < 1 g (push) to > 1 g (pull) loads. During a push, blood shifts towards the head. The carotid baroreceptors sense this shift and respond by decreasing heart rate (HR). In addition, vasomotor tone may increase in order to restrict the headward shift (8). This relative bradycardia may delay the onset of the cardiovascular compensatory response needed to tolerate a subsequent exposure to a +Gz-load. It is postulated that the potential danger of the "push-pull effect" (PPE) is two-fold: (1) the transition could lead to G-induced Loss of Consciousness (G-LOC); and (2) the event may initiate Almost-Loss of Consciousness (A-LOC) symptoms, including confusion, frustration, and/or uncontrollable muscle tremors without losing consciousness.

This phenomenon is not new. Early flight surgeon manuals warned of the dangers of following -Gz with +Gz. Aerobatic flight maneuvers, such as the Vertical "8", incorporated negative-to-positive G and pilots were lost when their aircraft "inexplicably" crashed during air shows (3). In 1954, Von Beckh (4) found that, during a transition from 0 to +6.5 Gz, subjects were disoriented, visual blackout lasted longer, and eye-hand coordination deteriorated more than during solely +Gz exposures. In his 1958 study (5), nine subjects flew in a two seat Lockheed F-94C (51 missions total) to determine the physiological reactions to +4 to +6.5 Gz loads both preceded and succeeded by 35 to 45s of weightlessness. Of two subjects who maintained vision during the control (+5 Gz) run, one blacked out at +4 Gz and the other lost total vision at +3.5 and experienced G-LOC at +5 Gz. Three who did blackout during control runs, blacked out at lower +Gz loads and shorter G durations. A 1992 centrifuge study (6), indicated that a 2s -1 Gz exposure reduced relaxed +Gz-tolerance by +0.77 Gz. An in-flight study (7) demonstrated that mean systolic BP (SBP) decreased after a transition from -2.5 to +4 Gz.

It is unknown whether the G-loads generated in a helicopter will produce the same effect as in tactical aircraft. Note that helicopter aircrew are not trained to perform anti-G straining maneuvers and their garments do not incorporate G-protection. Furthermore, PPE research has focussed on study of the phenomenon as an isolated event, i.e., expose subjects to different -Gz and +Gz levels, durations, and G-transition rates as discrete runs, not as part of mission scenario. The relevant operational issue is not only if an individual push-pull maneuver presents a G-LOC threat, but whether PPE contributes to decreased cardiovascular response over the course of an entire mission. The goals of this study were to determine if: (1) PPE presents a physiologic threat to helicopter aircrew by simulating mission scenarios which include current and projected helicopter acceleration capabilities; and (2) the physiologic response changed due to the cumulative effect of Gz exposure during these conditions. The study was conducted at the Veridian Operations Human Centrifuge Facility in Warminster, Pennsylvania.

METHODS

Subjects

Two women (54.7 ± 0.4 kg body weight, 165.1 ± 0.0 cm height, 34.5 ± 3.5 yr., 28.8 ± 0.4 cm eye-heart distance) and seven men (75.0 ± 9.9 kg body weight, 174.2 ± 4.8 cm height, 31.9 ±

4.1 yr., 28.9 ± 2.1 cm eye-heart distance) volunteered for this study. (Eye-heart distance was measured from the level of the aortic valve (third intercostal space) to the ectocanthus (9)). Subject relaxed G-tolerance (no anti-G suits or anti-G straining) was 4.5 ± 0.7 Gz (females) and 4.2 ± 0.8 Gz (males). Subjects wore summer flight coveralls and no anti-G suit. Subject informed consent was obtained in accordance with SECNAVINST 3900.38B and all pertinent Department of Health and Human Services regulations.

Measurements

Subjects wore two sets of electrocardiographic leads (sternal and biaxillary) to monitor HR. BP was recorded using a Finapres finger cuff device (Ohmeda Model 2300, Louisville, CO). Estimates of head level BP were obtained by positioning the hand at shoulder level with the arm supported in a custom designed sling. The distance between the finger cuff and ectocanthus was recorded before and after each centrifuge insertion.

Subjects verbally reported visual field decrements by monitoring light emitting diodes (LED's) placed in the centrifuge gondola at 15° increments from a central LED situated directly in front of the subject. Visual endpoints were defined as 60° loss of peripheral vision (PLL) or greater than 75% overall loss of vision. Subjects were instructed not to perform anti-G staining maneuvers since helicopter aircrew are not taught to strain. However, since the natural response to +Gz-stress is to tighten the muscles, subjects were instructed to tense their muscles and/or grunt to "clear their lights." Subjects estimated fatigue and nausea levels throughout the insertion using a modified Borg scale (10).

Acceleration Profiles

Push-Pull Mission (PPM)

During the first 25 min of each 60 min centrifuge insertion, the centrifuge was programmed to simulate the G-loads and onset/offset rates consistent with current capabilities of U.S. Navy aircraft (range: -0.2 to +3.5 Gz). This period was referred to as Current Mode (CM). Following a 5 min rest, the maneuver sequence was repeated with the same onset/offset rates but with G-loads scaled to represent the capabilities of future, more aggressive, platforms (range: -1.0 to +4.5 Gz). This phase was called Future Mode (FM). To minimize the effects of motion sickness during centrifuge push-pull transitions, the gondola was tilted back providing a constant +1.5 Gx bias, a technique used successfully in previous push-pull studies (11). The acceleration profiles were based on recordings of maneuvers taken from Apache, Black Hawk, and BK-117 aircraft. All maneuvers began from a base plateau of +1 Gz and are shown in figures 1 through 4.

(*FIG. 1 AND 2 HERE*)

<u>Gradual Onset Run</u> (GOR) (**Fig. 1**) is a purely +Gz maneuver based on an Apache profile, featuring a 0.1 g/s onset rate to a +2.5 Gz (FM: +4.5 Gz, **Fig. 2**) 5s plateau with a 0.2 g/s offset rate. Subjects were exposed to GOR at the beginning and end of both CM and FM. (Overall duration: CM: 34s, FM: 63s.)

Rapid Onset Run (ROR) (**Fig. 1**) is a push-pull maneuver based on an Apache profile. ROR begins with a push at 0.1 g/s to a +0.6 Gz 6s plateau, followed by a 1.0 g/s rise to +1.0 Gz. Then there is a pull at 1.25 g/s to a +3.5 Gz (FM: +4.5 Gz, **Fig. 2**) 2s plateau followed by a 0.56 g/sec offset rate. There were three repetitions of ROR during each mode sequence (Overall duration: CM and FM: 30s.)

Pushover (PO) (**Fig. 1**) is based on a pull-push-pull-push-pull BK-117 profile. During CM, the sequence has two pushes to +0.5 Gz and a peak pull to +2.25 Gz. In the FM (**Fig. 2**), the pushes reached -1 Gz and the maximum pull was +3.5 Gz. (Overall duration: CM: 28s, FM: 39s.)

"Modified" Lazy Eight (L8) (**Fig. 1**) is based on a BK-117 profile including a brief push, pull, longer push, followed by a pull with 21s (42s FM, **Fig. 2**) of varying +Gz levels. The second push reached +0.5 Gz (FM: -1 Gz) with a peak pull of +2.5 Gz (FM: +4.5 Gz). (Overall duration: CM: 50s, FM: 68s.)

Low/High Rapid Maneuver (LHR) (**Fig. 1**) is a pull-push-pull Black Hawk maneuver. The sequence is a 0.18 g/s rise to +1.9 Gz (FM: +3.0 Gz, **Fig. 2**), 0.34 g/s push to +0.1 Gz (FM: -1.0 Gz), and a 0.62 g/s pull to +3.0 Gz pull (FM: +4.5 Gz). (Overall duration: CM: 35s, FM: 61s.)

(*FIG. 3 AND 4 HERE*)

Low/High Gradual Maneuver (LHG) (**Fig. 3**) is an Apache pull-push-pull maneuver. This sequence starts with a 0.1 g/s pull to +1.4 Gz (FM: +2.0 Gz, **Fig. 4**), 0.19 g/s push to +0.26 Gz

(FM: -1.0 Gz), second pull at 0.17 g/s to +2.81 Gz (FM: +4.5 Gz), then returning to base plateau at 0.25 g/sec. (Overall duration: CM: 52s, FM: 93s.)

Ridgeline Crossing (RLC) (**Fig. 3**) is a pull-push-pull BK-117 sequence derived from low-level terrain following maneuvers. The minimum plateaus were -0.2 Gz (FM: -1.0 Gz, **Fig. 4**) and peak loads were +1.75 Gz (FM: +2.5 Gz). Since RLC was a relatively short profile, it was repeated twice with an 18s rest at +1 Gz between repetitions. (Overall duration: CM: 48s, FM: 66s.)

Loop (**Fig. 3**), also based on a BK-117 profile, is very similar to RLC. The push phases reach +0.5 Gz (FM: -0.5 Gz, **Fig. 4**) while the peak pull is +2.5 Gz (FM: +3.5 Gz). Loop was also repeated twice with 32s at +1 Gz between repetitions. (Overall duration: CM: 80s, FM: 92s.)

Hammerhead (HH) (**Fig. 3**), was the last of the BK-117 pull-push-pull maneuvers. It has a variety of intermediate steps, but has a peak pull of +2.25 Gz (FM: +3.25 Gz, **Fig. 4**) and a push of +0.25 Gz (FM: -1.0 Gz). HH was repeated twice with 32s at +1 Gz between maneuvers. (Overall duration: CM: 80s, FM: 84s.)

For both CM and FM, the sequence of maneuvers during an insertion was GOR1, ROR1, PO, L8, LHR, ROR2, LHG, ROR3, two RLC's, two Loops, two HH's, and GOR2. The GOR and ROR maneuvers were repeated to determine if the physiological response to these profiles changed over time, thereby providing an index of the effects of cumulative G-stress.

+Gz MISSION (GM)

During GM, subjects experienced the same mission scenario outlined in PPM except that all push transitions were fixed at +1.0 Gz for both CM and FM. The +Gx bias, timing, and onset/offset rate transitions were identical. As an example, **Fig. 5** shows the CM GM. Overall, subjects were randomly exposed to two PPM and two GM insertions during one week.

Data Analysis

Light loss estimates were averaged for each mission type and differences determined using repeated measures ANOVA ($\alpha = 0.05$) (using subject as a random variable and light loss, mission (PPM or GM), and maneuver as fixed variables) and source of those differences assessed with a post-hoc Fisher's Least Squares Difference (LSD) Multiple-Comparison test (Number Cruncher Statistical Systems 97, JL Hintze, Kaysville, Utah). (A student's t-test indicated no gender differences.) Mean scores for fatigue and nausea were calculated for each subject for each mission and mode and compared using Wilcoxon Signed-Rank Test for Difference in Medians.

Given the within and between subjects variability in HR and BP during a given maneuver (with each data point occurring anywhere from 0.36 to 0.82s), the data were first aligned with the acceleration profiles. For example, each maneuver was segmented into a series of fiducial points, such as the beginning of a push transition, the start and end of a plateau, etc. Then, BP data for each subject were organized relative to those points in order to compare the responses for a given maneuver and mission. In cases where HR was faster (i.e. more BP samples) between a given pair of points during one mission than another (e.g., ROR PPM pull phase versus GM), pairs of consecutive BP values were averaged (thereby equalizing the number of BP points for a given epoch). In this fashion, BP responses at the same G level and time during a given maneuver could be compared. To normalize the data, the change in SBP (ΔSBP) for each maneuver was determined relative to a 10s average calculated during the rest phase immediately prior to that maneuver. Repeated measures ANOVA (followed Fisher's LSD post-hoc test) was used to determine if there were significant differences in ΔSBP based on mission (PPM versus GM), mode (CM versus FM), and in the case of ROR and GOR, on succeeding repetitions of the same profiles. To process the ANOVA, a factor was used to segment each portion of the maneuver, in order to distinguish responses based on different G transitions (push or pull) within a given maneuver. For example, CM ROR was segmented into 24 points based on the push phase (3 points during the transition from +1 to +0.6 Gz, 4 points during the +0.6 Gz plateau, and 3 points during the return to +1 Gz), the pull phase (4 points during the rise to the +3.5 Gz plateau and at its peak), the offset to +1 Gz (6 points), and during 10s of recovery (4 points at +1 Gz). In this manner, responses to G-stress were tested for differences in ΔSBP approximately every second. HR analysis was performed in the same fashion as the BP data.

RESULTS

Subjective Measures (Light Loss, Fatigue, Nausea)

Virtually no light loss occurred during CM for GM and PPM, except during the ROR's. PLL during ROR3 ranged from 30° to 10% to 40% overall gray. Subjects reported that light loss occurred during the push to pull transition. No subjects required muscle tensing during these runs to maintain vision.

Since there were no significant differences in PLL between the two PPM insertions or between the two GM, mean reported light loss was analyzed (Table II). Overall, light loss was significantly greater during PPM than GM ($F = 5.94$, $p = 0.041$). There was also an interaction between type of mission and maneuver ($F = 3.51$, $p = 0.002$). To clarify the source of these differences, additional ANOVA focussing on the individual maneuvers. Light loss was significantly greater during the PPM PO and L8 as compared to the GM ($F = 12.66$, $p = 0.007$ and $F = 8.89$, $p = 0.018$, respectively), whereas light loss differences during GORs (relative to mission mode or over time) or for LHR and LHG were not significant. While mean light loss increased during each succeeding PPM ROR, the increases were not statistically significant.

(TABLE II HERE)

Subjects required some level of straining to maintain their vision during FM GOR, ROR, LHR, and LHG maneuvers. The amount of effort varied between individuals, with the ROR, LHR, and LHG maneuvers requiring the most. The two female subjects often used an effective breathing technique similar to a Lamaze pattern, i.e., short exhaled puffs.

There were no significant differences in subjective fatigue or nausea ratings between the two PPM insertions or between the two GM trials. While it was shown that subjective fatigue and nausea ratings were statistically greater during FM versus CM (PPM: Z value = 3.86, $p < 0.001$; GM: Z value = 6.08, $p < 0.001$), as well as fatigue during CM PPM versus GM (Z value = 4.39, $p < 0.001$), the absolute rating values indicated that mean fatigue and nausea levels were just "noticeable".

Cardiovascular System Response

Since there was minimal PLL during RLC, Loop, and HH, cardiovascular data analysis excluded these maneuvers.

Current Mode ROR

The drop in ΔSBP during the pull phase of CM ROR increased with each succeeding repetition of the ROR. Mean peak ΔSBP during PPM were -8.1 (ROR1), -11.0 (ROR2), and -12.8 mmHg (ROR3) and -3.9 (ROR1), -6.6 (ROR2), and -7.8 mmHg (ROR3) during GM. ΔSBP dropped faster over time from –2.4 to -4.4 mmHg/s (PPM) and –1.3 to -2.1 mmHg/s (GM) between ROR1 to ROR3. There was a statistically significant difference in ΔSBP between PPM and GM ($F = 2.58$, $p < 0.001$) and overall between ROR1 when compared to ROR2 and ROR3 ($F = 22.82$, $p < 0.001$).

Mean CM ROR1 ΔHR was slightly greater than ROR2 and ROR3 for both PPM and GM ($F = 3.54$, $p = 0.029$). Subject pool mean maximum rise in ΔHR during PPM was 22.0 (ROR1), 20.1 (ROR2), and 19.8 bpm (ROR3) and 17.4 (ROR1), 18.7 (ROR2), and 16.5 bpm (ROR3) during GM. While the decrease in ΔHR during the push phase was greater during PPM relative to GM ($F = 1.78$, $p = 0.013$), the magnitude was quite small (mean ΔHR: PPM: -2.9 ± 2.0 bpm; GM: -0.7 ± 1.7 bpm). The overall change in HR between push minimums and pull maximums during PPM were 29.3 (ROR1), 35.3 (ROR3), 31.1 bpm (ROR3) and for GM were 31.7 (ROR1), 28.6 (ROR2), 26.5 bpm (ROR3).

Future Mode ROR

Unlike the CM ROR, ΔSBP during the pull phase of FM ROR1 was greater than ROR2 and ROR3. Mean peak changes during PPM were -26.2 (ROR1), -21.5 (ROR2), and -22.9 mmHg (ROR3) and -19.5 (ROR1), -23.8 (ROR2), and -19.7 mmHg (ROR3) during GM. PPM ΔSBP changed faster than GM, from –5.3 to -4.8 mmHg/s (PPM) and –3.5 to -4.4 mmHg/s (GM) between ROR1 to ROR3. There was a significant difference in ΔSBP between PPM and GM ($F = 3.43$, $p < 0.001$) during the pull phase and over time during ROR1 relative to ROR2 and ROR3 ($F = 6.39$, $p = 0.002$). **Fig. 6** shows the difference between PPM and GM ROR1. The horizontal dotted line indicates -22 mmHg which, according to the hydrostatic column theory of G tolerance, corresponds to a 1 g drop in +Gz tolerance (12).

The overall increase in ΔHR was slightly less during ROR1 as compared to ROR2 and ROR3 for both PPM and GM ($F = 6.42$, $p = 0.002$). Mean maximum HR increase during PPM was 32.2 (ROR1), 35.4 (ROR2), and 34.9 bpm (ROR3) and 28.1 (ROR1), 32.4 (ROR2), and 28.3 bpm (ROR3) during GM. While the decrease in PPM push ΔHR was greater than GM ($F = 2.01$, $p = 0.001$), the magnitude was quite small (mean ΔHR: PPM: -3.1 ± 2.9 bpm; GM: 0.5 ± 1.8 bpm). **Fig. 7** details the differences between PPM and GM ROR3. Increases in ΔHR above 25 bpm are indicated by the horizontal line.

Current Mode GOR

A GOR at the beginning and end of each mode segment was included to determine if (1) the cardiovascular response to the second GOR after the intervening 10 profiles differed from the first (presumably from fatigue) and (2) that response was different if the 10 profiles were PPM or GM maneuvers. For both CM missions, while the decline in ΔSBP was greater during GOR2, the drop was significant only during GM ($F = 5.91$, $p = 0.015$). However, the reduction in ΔSBP were small (4.4 mmHg (PPM); 5.6 mmHg (GM)). Interestingly, SBP rose faster during the rise to peak +Gz during GOR2 than GOR1 during both PPM (0.18 Vs. 0.10 mmHg/s (65%)) and GM (0.29 Vs. 0.23 mmHg/s, (31%)). There were no statistical differences demonstrated when comparing PPM Vs. GM ΔSBP or ΔHR. Peak ΔHR were 10.9 (PPM) and 12.4 bpm (GM).

Future Mode GOR

ΔSBP dropped further during GOR2 as compared to GOR1 for both PPM and GM ($F = 112.72$, $p < 0.001$). Furthermore, the decrease in ΔSBP during GM GOR2 was greater than during PPM ($F = 18.04$, $p < 0.001$). The peak decrease in ΔSBP during GM was -12.2 (GOR1) and -16.0 mmHg (GOR2) while during PPM it was -10.9 (GOR1) and -14.1 mmHg (GOR2). The increase in ΔHR was greater during GOR2 Vs. GOR1 during both PPM and GM ($F = 5.45$, $p = 0.020$), particularly during the +Gz peak, offset and recovery phases of the maneuver. Peak ΔHR ranged from 26.7 (GOR1) to 37.7 bpm (GOR2) for PPM and 36.3 (GOR1) to 40.1 bpm (GOR2) during GM. HR recovery rate decreased over time from -1.12 (GOR1) to -0.86 bpm/s (GOR2) during PPM (24%) and -1.84 (GOR1) to -1.19 bpm/s (GOR2) during GM (35%). Overall, ΔHR during GM was statistically greater than during PPM ($F = 27.05$, $p < 0.001$), although the mean difference was only 2.6 ± 0.4 bpm.

Low/High Rapid Maneuvers

In the low/high maneuvers, the effect of transition rate during pull-push-pull maneuvers were assessed. During the first pull SBP falls (HR rises), with the push SBP rapidly rises (HR falls), and with the second pull SBP falls (HR accelerates), only to rise again with the offset from the second peak. Overall, there were no significant differences based on type of CM mission for LHR ΔSBP or ΔHR. For example, the peak decrease in ΔSBP was 7.3 mmHg for both PPM and GM. Maximum and minimum ΔHR were similar for PPM and GM (PPM: +11.9 and -13.9 bpm; GM: +9.3 and -13.5 bpm).

The peak decrease in FM ΔSBP was comparable ($p > 0.05$) between both missions (PPM: -18.3 mmHg; GM: -21.4 mmHg), though the hyperemic response during recovery of SBP was greater during PPM (10.4 mmHg) than GM (4.4 mmHg). However, the decrease in PPM ΔHR during the push phase and the increase during the subsequent pull were significantly different than GM ($F = 3.12$, $p < 0.001$). Minimum ΔHR during the push was -28.2 (PPM) and -10.3 bpm (GM) and maximum ΔHR during the subsequent pull was +39.0 bpm (PPM) and +26.8 bpm (GM). During the push phase, whereas GM ΔHR fell at -2.9 bpm/s then remained close to pre-run levels (-3.7 ± 5.2 bpm) while at +1 Gz, PPM ΔHR dropped at -4.1 bpm/s, reaching a minimum at -1 Gz (averaging -12.2 ± 10.1 bpm while under +1 Gz). **Fig. 8** details the differences between PPM and GM. Increases in ΔHR greater than 25 bpm are indicated above the horizontal line.

Low/High Gradual Maneuvers

With slower G transition rates, LHG ΔSBP followed with same pattern as during the LHR. The maximum decline in CM ΔSBP was similar ($p > 0.05$) for both missions (PPM: -8.8 mmHg; GM: -9.8 mmHg). Maximum (during the second pull) and minimum (during the push phase) CM ΔHR were comparable ($p > 0.05$) for PPM and GM (PPM: +16.1 and -14.8 bpm; GM: +14.9 and -9.6 bpm). Throughout the push phase, the mean PPM ΔHR was -8.1 ± 5.4 bpm and -3.4 ± 3.6 bpm for GM.

While the overall decline in FM ΔSBP was greater during PPM, there were no statistical differences between PPM and GM ΔSBP. The maximum decline in ΔSBP was similar for both missions (PPM: -15.3 mmHg; GM: -14.7 mmHg). However, the decrease in PPM ΔHR during the push phase was significantly greater than GM ($F = 4.11$, $p < 0.001$), reaching a minimum of -25.8 bpm (PPM) and -10.0 bpm (GM). Note that PPM and GM ΔHR fell at the same rate (-2.1

bpm/s). Maximum ΔHR during the subsequent pull were comparable (PPM: +40.4 bpm; GM: +39.3 bpm).

Pushover Maneuver

As with the other pull-push-pull type maneuvers, ΔSBP followed the general changes in Gz-stress during the Pushover, with a slightly greater overall decline in ΔSBP during PPM. There was no apparent effect of the modest pull between the two pushes in mean CM ΔSBP. No statistical differences between PPM and GM ΔSBP or ΔHR were found. The maximum decline in ΔSBP was slight for both missions (PPM: 4.2 mmHg; GM: 2.8 mmHg). Minimum ΔHR were attained during the second push (PPM: -10.8 bpm; GM: -11.2 bpm) and peak ΔHR occurred during the final pull (PPM: 10.6 bpm; GM: 7.8 bpm).

The drop in ΔSBP during FM PO was greater during PPM than GM ($F = 1.62$, $p = 0.023$). These differences were attributed to responses during the transition between the push and second pull phases of the maneuver and during recovery after the peak of the second push, as shown in **Fig. 9**. The maximum decline in ΔSBP was -17.0 mmHg (PPM) and -15.9 mmHg (GM). ΔSBP fell faster during PPM between the push and the second pull (0.99 mmHg/s) and took longer to recover after the second pull (1.66 mmHg/s) than GM (0.83 mmHg/s and 2.07 mmHg/s, respectively). Also during the push phases, the decrease in FM PPM ΔHR (-19.6 ± 2.9 bpm) was significantly greater ($F = 4.28$, $p < 0.001$) than GM (-8.4 ± 2.8 bpm). During the final pull, PPM ΔHR reached 21.4 bpm at 4.1 bpm/s while GM ΔHR peaked at 17.9 bpm at 2.6 bpm/s.

Modified Lazy 8 Maneuver

The L8 maneuver featured a low +Gz pull, followed by a push and an extended higher +Gz exposure. No statistical differences between CM PPM and GM ΔSBP or ΔHR were demonstrated. Minimum (PPM: -4.9 mmHg; GM: -3.6 mmHg) and maximum (PPM: 0.94 mmHg; GM: 2.49 mmHg) ΔSBP were comparable. ΔHR range was slightly greater during PPM ($-11.5 \le \Delta HR \le 8.7$ bpm) than GM ($-8.7 \le \Delta HR \le 9.0$ bpm).

During FM L8, the overall drop in ΔSBP was slightly greater during PPM (-14.9 mmHg) than GM (-13.1 mmHg). There was a marginal difference between missions ($p = 0.52$), primarily due to the rate of change in ΔSBP following the push phase (PPM: 2.20 mmHg/s; GM: 1.53 mmHg/s) and the subsequent rise in ΔSBP during the extended +Gz phase (PPM: 0.87 mmHg/s; GM: 0.74 mmHg/s). FM ΔHR was significantly different between PPM and GM ($F = 3.28$, $p < 0.001$). This was based on the ΔHR during the push (PPM: -17.8 ± 6.1 bpm; GM: -3.1 ± 0.7 bpm) and ΔHR during the second of the +3.5 Gz plateaus after the push (PPM: 29.9 ± 2.1 bpm; GM: 20.9 ± 1.3 bpm).

Almost-Loss Of Consciousness (A-LOC)

There were four instances in which subjects reported A-LOC symptoms. During his second PPM insert, one subject reported that he had a "harder time concentrating today." It was "harder to remember the profile details after about 15 min into the insertion." It "was frustrating." Another male subject reported that he "did not feel clearheaded" during his second PPM insert.

A third subject, during his first GM exposure with the FM Loop maneuver, stated that he had a "warm feeling" accompanied by a "don't care attitude" which "came on suddenly." He reported that he was "not paying attention." The feeling passed by the end of the insert. The final incident occurred to a fourth subject during his first GM exposure to the FM ROR3 maneuver. He reported being confused and "started to reach for the (stop the run) switch, but was unsure why" he wanted to.

DISCUSSION

For an average male, mean SBP at heart level is 120 mmHg at 1 g. The heart must overcome an approximately 30 cm column (22 mmHg hydrostatic pressure) for blood to reach the head. For each 1 g increase in applied +Gz stress, head level pressure drops another 22 mmHg (12). Light loss symptoms appear at approximately 50 mmHg head-level BP (13). Stauffer found that the onset of visual symptoms of 215 relaxed male subjects occurred at +3.7 Gz (14). In a study using tilt table exposures, Schellong defined the onset of orthostatic hypotension as a ΔSBP of 21 mmHg (15). Therefore, given the acceleration levels employed in this study, a decrease in ΔSBP measured at shoulder height of approximately 20 mmHg, equivalent to about a 1 g loss in G-tolerance, is considered a significant.

In a study examining the HR response of 30 male pilots to GOR exposures (the standard +Gz training profile used to maximally challenge the cardiovascular system), the threshold for significant HR change was 25 bpm (16). Therefore, this benchmark was used to gauge operationally significant changes in HR.

The methodology presented in this report represents the first systematic attempt to study the cardiovascular response to PPE utilizing Gz-loads and transitions based on actual flight maneuvers. ΔSBP and ΔHR observed were consistent with tactical in-flight measurements reported by Prior (7). An analysis approach which identifies the cardiovascular response to particular G transitions within a given maneuver also represents a new approach.

CM: Subjects experienced little light loss and did not need to strain to finish their CM runs. Note that when light loss was reported, it typically occurred during the transition from push to pull. However, modest decrements in visual field may become more significant when aircrew wear helmet mounted displays. For individuals who experience an overall graying or decrease in acuity rather than classic PLL, it is possible that viewing certain symbology, colors, or intensities may be impaired.

Only during the ROR were there statistically significant differences in ΔSBP between PPM and GM. Peak ΔSBP for all maneuvers were well below 20 mmHg, reaching a maximum decrease of 12.8 mmHg during ROR3. It appeared that the cardiovascular system was progressively taxed during the 25 min CM mission based on the significant reduction in ROR ΔSBP over time.

Likewise, only the differences in ΔHR between ROR CM PPM and GM were statistically significant. The maneuvers in which overall change in HR between push and pull phases were physiologically significant were the ROR (PPM: 35.3 bpm; GM: 31.7 bpm) and the low/high maneuvers (LHR: PPM = 25.8 bpm, GM = 22.8 bpm; LHG: PPM = 30.9 bpm, GM = 25.5 bpm). The cardiovascular system did respond to the applied stress by increasing ΔHR more quickly during PPM as compared to GM mission.

Given the relatively small change in SBP and minimal light loss, the cardiovascular response to the relatively low CM Gz-loads, as indicated by ΔHR, is probably sufficient to enable aircrew to tolerate these exposures. This would apply for relatively short missions for aircrew who are sufficiently hydrated. However, given that differences in cardiovascular response between PPM and GM were demonstrated and the apparent effect of time in the level of response, it is possible that aircrew on longer missions may be at risk. Specific data would have to be collected for longer exposures and include determining the effects of dehydration and the impact of increased thermal burden associated with wearing impermeable protective garments.

FM: Loss of vision was considerably greater during the FM mission as compared to the CM. Light loss during PPM was greater than GM and subjects needed to exert a marginally greater level of muscular tensing to keep their vision clear, as well. Light loss was greatest during the transition from push to pull, particularly during maneuvers featuring a 5.5 Gz transition, such as the ROR and Low/High runs.

The decrease in SBP was significantly greater during PPM ROR and PO maneuvers when compared to GM. These differences occurred during the relatively large magnitude +Gz pull following the push phase in both maneuvers. Furthermore, as the time at G increased, the drop in ΔSBP is also significantly greater, as was demonstrated by comparing GOR2 with GOR1 and

ROR2 and ROR3 with ROR1. During the ROR, peak declines in ΔSBP were above 20 mmHg for both PPM and GM, indicating that G-tolerance declined by approximately 1 g. Overall, peak drop in ΔSBP during maneuvers other than GOR ranged from -13.1 to -21.4 mmHg, a drop in G-tolerance from about 0.6 to 1 g. The influence of G-transition rate was demonstrated by the observation that the decline in ΔSBP during LHR was greater than during LHG. This is probably because the slower rise during LHG allowed time to invoke a greater cardiovascular compensatory response than during the LHR.

During the FM runs, PPM ΔHR was statistically greater than during GM, for ROR, LHR, LHG, PO, and L8 maneuvers. ΔHR increased as time at G increased for both ROR and GOR runs. The peak overall ΔHR were physiologically significant, as follows: LHR: 67.2 bpm (PPM), 37.0 bpm (GM); LHG: 66.4 bpm (PPM), 49.3 bpm (GM); PO: 44.0 bpm (PPM), 36.0 bpm (GM); ROR: 46.5, 50.3, 52.6 bpm (PPM runs 1, 2, 3, respectively) and 49.9, 44.4, 50.1 bpm (GM runs 1, 2, 3, respectively); and GOR: 38.7, 43.1 bpm (PPM runs 1, 2, respectively), and 45.9, 42.2 bpm (GM runs 1, 2, respectively).

Given the physiologic responses to the stresses developed during FM exposures (relatively large decrease in SBP, significant increase in HR, loss of peripheral vision, incidences of possible A-LOC symptoms, and the increased need for muscular tension), aircrew exposed to Gz-loads developed by more aggressive platforms are at a greater risk than when flying conventional helicopters. Furthermore, exposures to push-pull maneuvers may have a somewhat greater risk than exposures to purely +Gz loads. Subjects noted that they felt a greater fatigue after PPM as compared to GM. In some instances, subjects' PLL reached 90°. However, given that all runs were completed without the need for performing anti-G straining maneuvers or with the support afforded by anti-G suits, indicates that these types of exposures are tolerable within the parameters set by this experiment. That is, an overall 60 min limit and exposure to the higher loads during the last half hour by subjects who were presumably euhydrated.

The findings of this study have important implications in the fixed wing tactical community as well. The significant changes in cardiovascular response, loss of visual field, and incidence of A-LOC episodes at these relatively low G levels could be expected to increase during tactical missions during which pulls may reach +7.5 to 9 Gz. In particular, the areas of helmet mounted displays, aircrew protection, and tactics may benefit from these data.

CONCLUSIONS

Within the scope of these tests, subjects had little difficulty tolerating the range of acceleration stresses associated with helicopters currently employed in the U.S. Navy inventory. As helicopter performance increases in the range of -1 Gz to +4.5 Gz (within the capabilities of current U.S. Army platforms), the associated cardiovascular stress significantly increases while the ability to tolerate the G-loads decreases. Aircrew may be at increased risk during longer high performance helicopter missions if aircrew are not given adequate training for this environment. It is important to note that even at these relatively low acceleration loads and transition rates, four separate instances of A-LOC occurred, two during PPM and two during GM. In each case, subjects reported deficits in the ability to concentrate. As such, the potential for performance degradation during rotary wing flight due to unprotected exposures to Gz-stress exists.

Based on the findings in this study, it seems prudent to recommend establishing a training program for helicopter aircrew about the potential hazards of acceleration loads (including PPE), such as the loss of vision, the need for muscular tensing/straining or breathing patterns to restore vision, and the potential for A-LOC.

Future studies should investigate (1) the effects on physiological responses and cognitive and psychomotor performance of cumulative G-stress during longer simulated missions based on operational needs and (2) the effects of dehydration on ability to tolerate helicopter Gz-stress, including the use of operational flight gear, and life support equipment, e.g. anti-exposure garments, CBR protection, and body armor.

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APPENDIX

Key to acronyms used:

A-LOC: Almost-Loss of Consciousness

CM: Current Mode (simulation including exposures between -0.2 to +3.5 Gz)

FM: Future Mode (simulation including exposures between –1.0 to +4.5 Gz)

G-LOC: G-induced Loss of Consciousness

GM: +Gz Mission (simulation with push transitions = +1 Gz)

GOR: Gradual Onset Run

HH: Hammerhead Maneuver

HR: Heart Rate

L8: "Modified" Lazy Eight Maneuver

LHG: Low/High Gradual Maneuver

LHR: Low/High Rapid Maneuver

PPM: Push-Pull Mission (simulation including transitions < +1 Gz)

PLL: Loss of Peripheral Vision

PPE: Push-Pull Effect

PO: Pushover Maneuver

RLC: Ridgeline Crossing Maneuver

ROR: Rapid Onset Run

SBP: Mean Systolic Blood Pressure

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TABLE I. OPERATIONAL G-LIMITS OF SELECTED HELICOPTERS

Aircraft	Name	G-range
OH-58	Kiowa	$+0.5 \rightarrow +2.8$
OH-58D	K Warrior	$+0.5 \rightarrow +2.8$
AH-1	Cobra	$+0.5 \rightarrow +2.4$
UH-60	Black Hawk	$-0.5 \rightarrow +3.0$
AH-64	Apache	$-0.5 \rightarrow +3.5$
RAH-66	Comanche	$-1.0 \rightarrow +3.5$
BK-117	*	$-0.2 \rightarrow +3.0$

*G-ranges for BK-117 were observed values during flight tests.

TABLE II. PLL (DEG) DURING FM PPM AND GM
(MEAN ± STANDARD DEVIATION AND MAXIMUM REPORTED).

Maneuver	Mean PLL (PPM)	Mean PLL (GM)	Max PLL (PPM)	Max PLL (GM)
GOR1	26 ± 17	22 ± 26	53	68
ROR1	41 ± 27	34 ± 28	70	73
PO	14 ± 17	0 ± 0	45	0
L8	40 ± 33	12 ± 16	85	38
LHR	56 ± 35	42 ± 31	83	75
ROR2	48 ± 31	48 ± 29	78	75
LHG	43 ± 37	37 ± 33	85	83
ROR3	50 ± 31	42 ± 29	90	75
RLC	1 ± 2	0 ± 0	5	0
LOOP	1 ± 2	0 ± 0	5	0
HH	2 ± 7	1 ± 2	20	5
GOR2	19 ± 26	26 ± 30	75	83

FIGURE CAPTIONS:

Fig. 1. Sequence of the first six maneuvers of the Push-Pull Mission during a Current Mode centrifuge insertion.

Fig. 2. Sequence of the first six maneuvers of the Push-Pull Mission during a Future Mode centrifuge insertion.

Fig. 3. Sequence of the last six maneuvers of the Push-Pull Mission during a Current Mode centrifuge insertion.

Fig. 4. Sequence of the last six maneuvers of the Push-Pull Mission during a Future Mode centrifuge insertion.

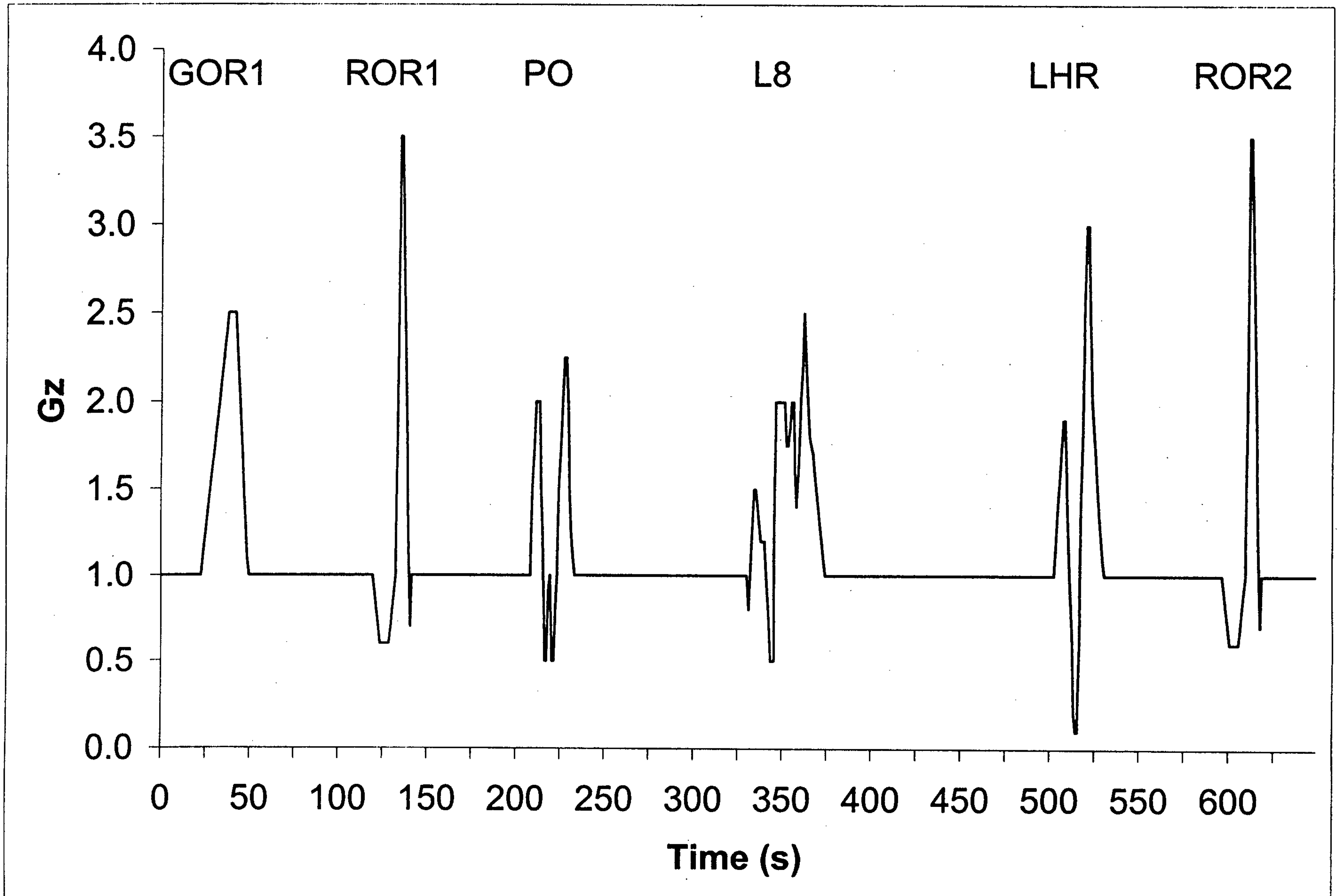
Fig. 5. Sequence of the +Gz-Mission maneuvers during a Current Mode centrifuge insertion.

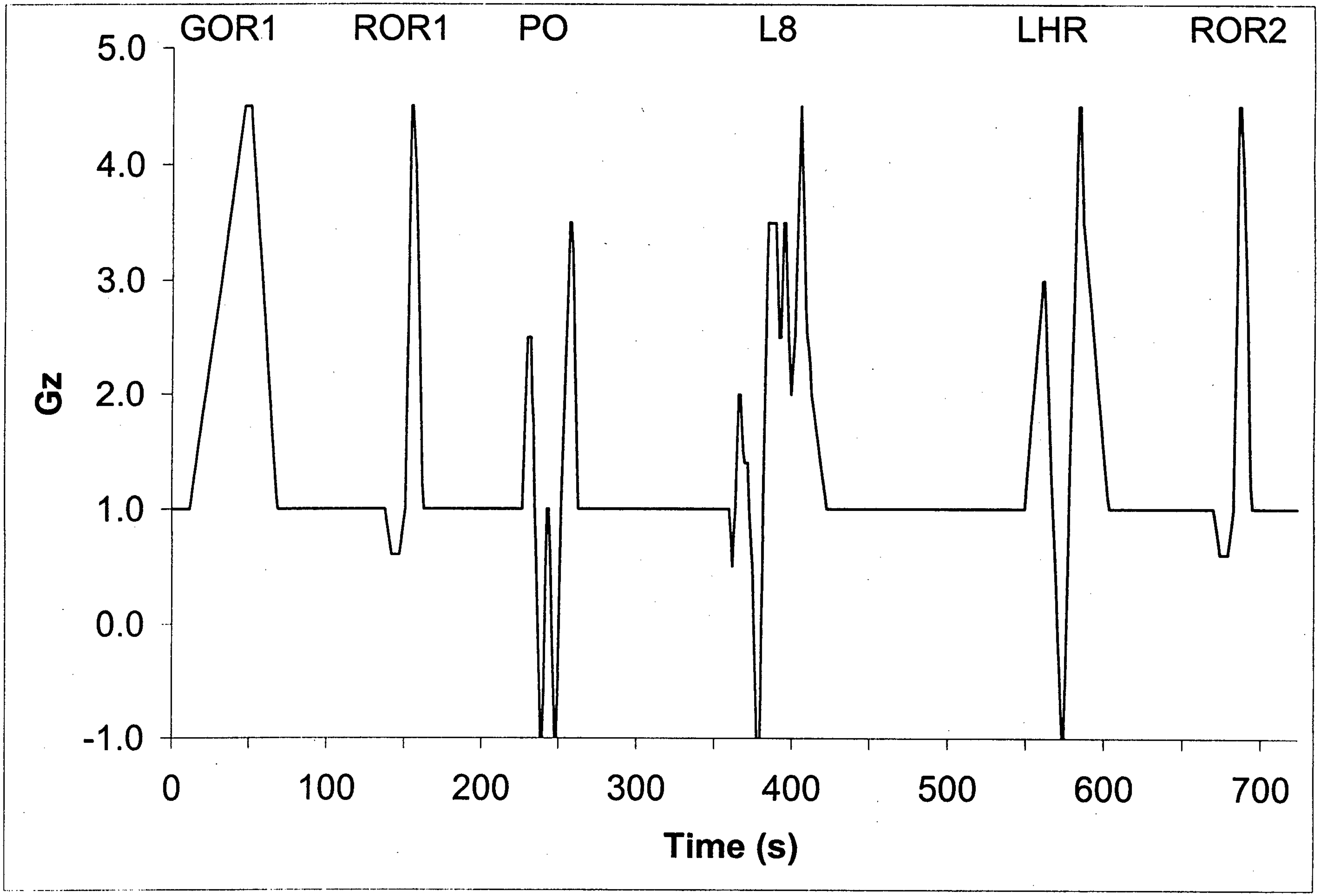
Fig. 6. Mean change in systolic blood pressure during the third ROR maneuver (ROR3) during a Future Mode segment of the Push-Pull Mission (PPM) and +Gz-Mission (GM). The Gz trace represents push-pull Gz-loads. A drop in ΔSBP of 22 mmHg (dotted line) represents a 1 G reduction in G-tolerance.

Fig. 7. Mean change in heart rate during the third ROR maneuver (ROR3) during a Future Mode segment of the Push-Pull Mission (PPM) and +Gz-Mission (GM). The Gz trace represents push-pull Gz-loads. An increase in ΔHR of 25 bpm (dotted line) is considered operationally significant.

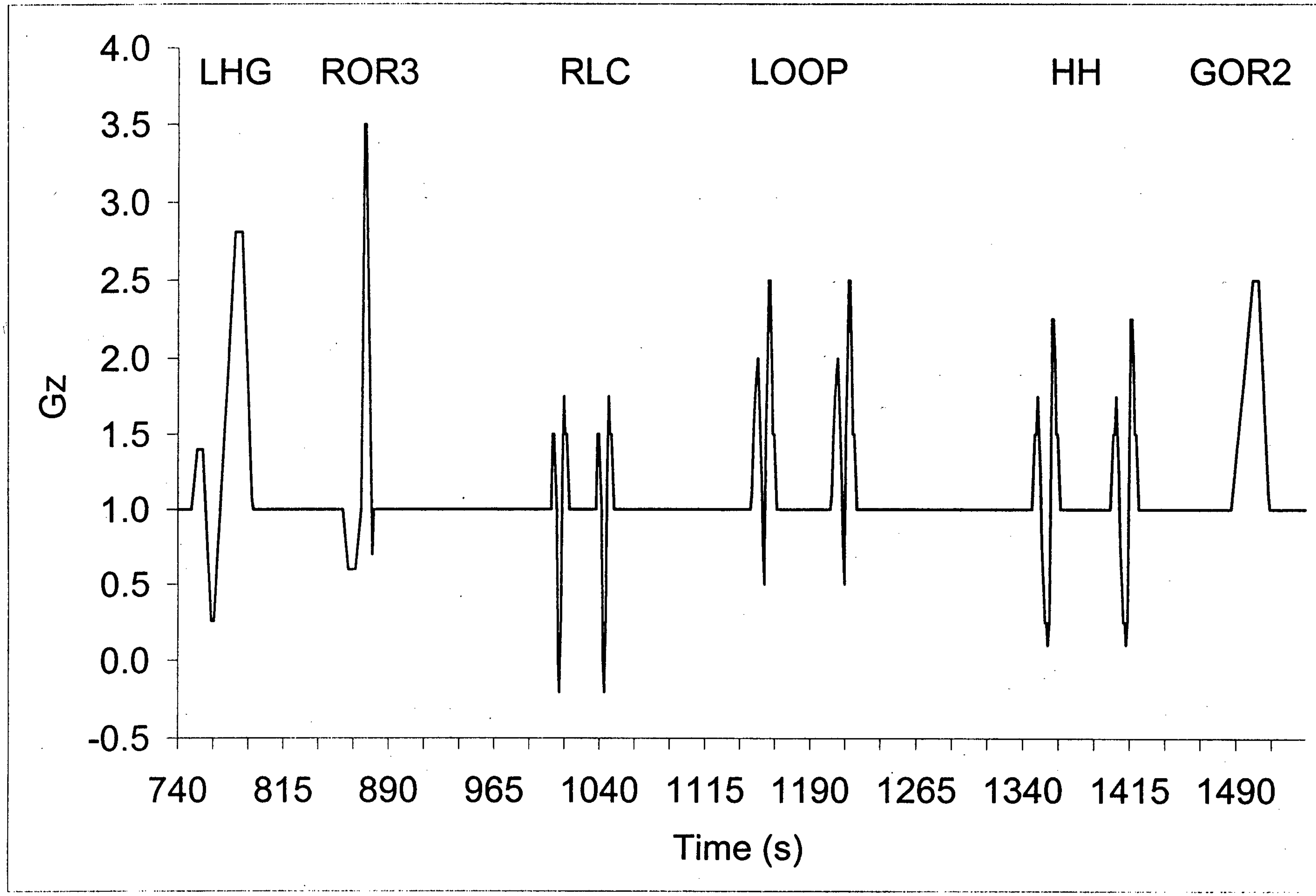
Fig. 8. Mean change in heart rate during the Low-High Maneuver (LHR) during a Future Mode segment of the Push-Pull Mission (PPM) and +Gz-Mission (GM). The Gz trace represents push-pull Gz-loads. An increase in ΔHR of 25 bpm (dotted line) is considered operationally significant.

Fig. 9. Mean change in systolic blood pressure during the Push Over Maneuver (PO) during a Future Mode segment of the Push-Pull Mission (PPM) and +Gz-Mission (GM). The Gz trace represents push-pull Gz-loads.


GOR1
ROR1
PO
L8
LHR
ROR2
Gz
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
250
300
350
400
450
500
550
600
Time (s)

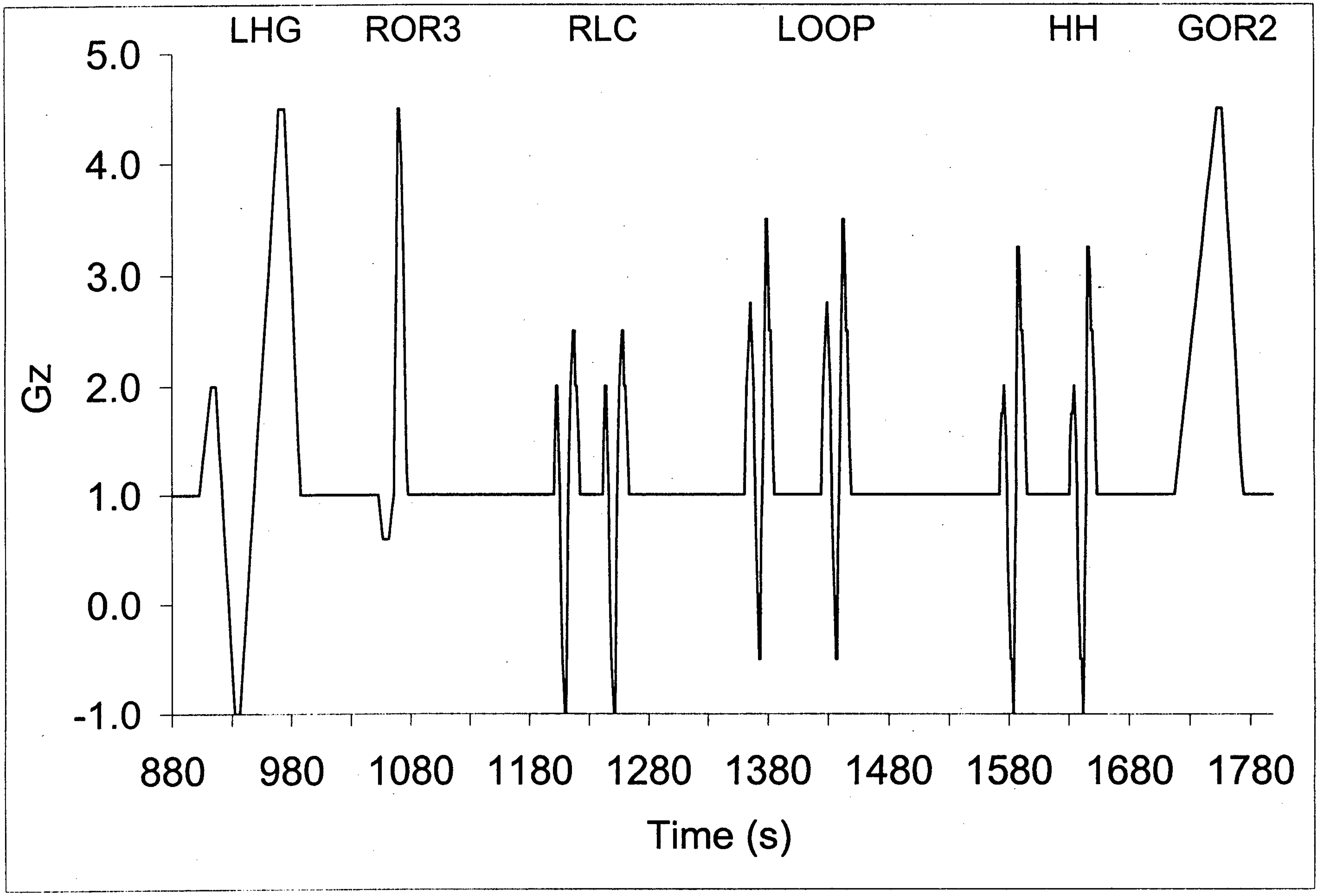


GOR1
ROR1
PO
L8
LHR
ROR2
Gz
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
0
100
200
300
400
500
600
700
Time (s)



LHG
ROR3
RLC
LOOP
HH
GOR2
Gz
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
740
815
890
965
1040
1115
1190
1265
1340
1415
1490
Time (s)

3


LHG
ROR3
RLC
LOOP
HH
GOR2
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4.0
3.0
2.0
1.0
0.0
-1.0
Gz
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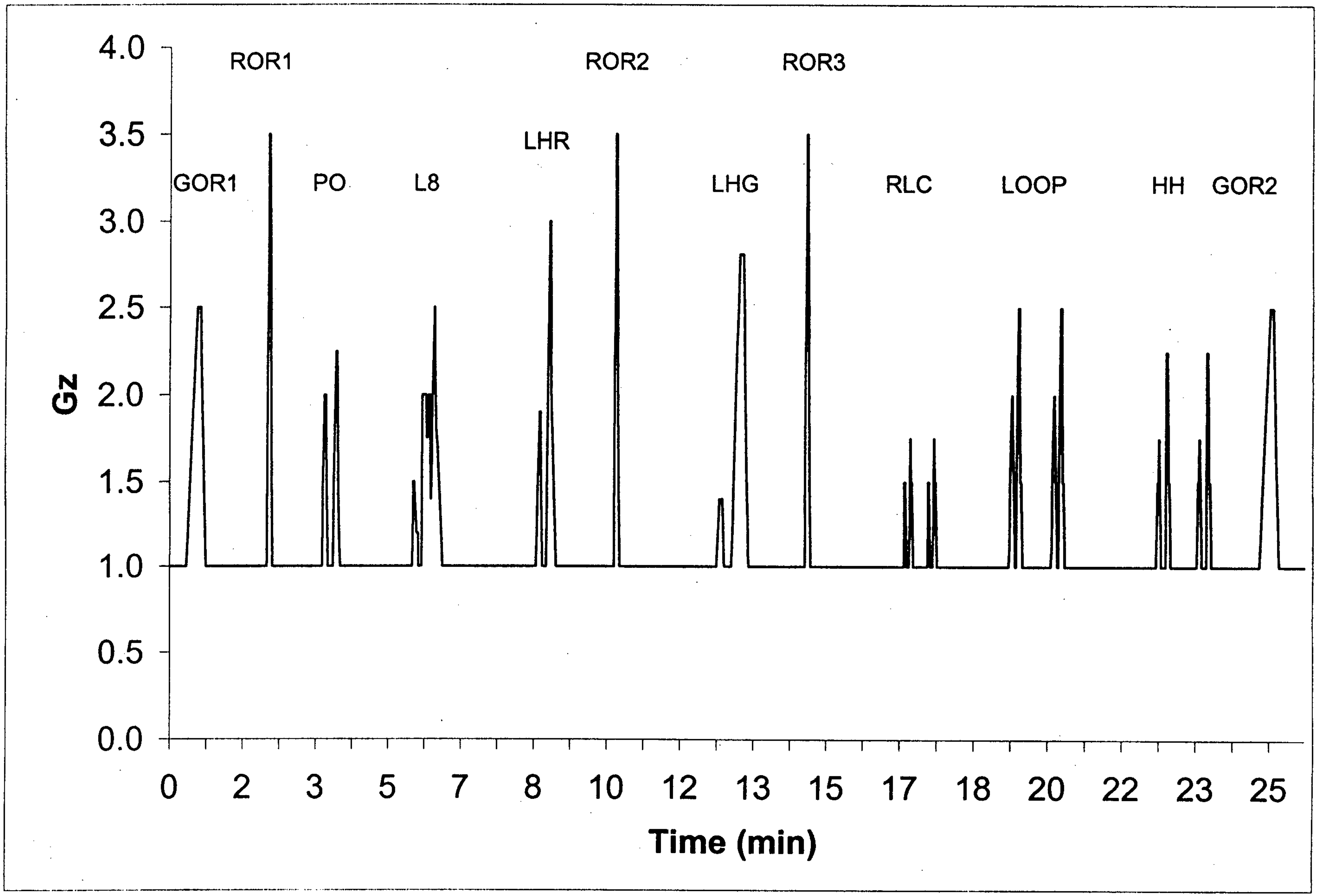
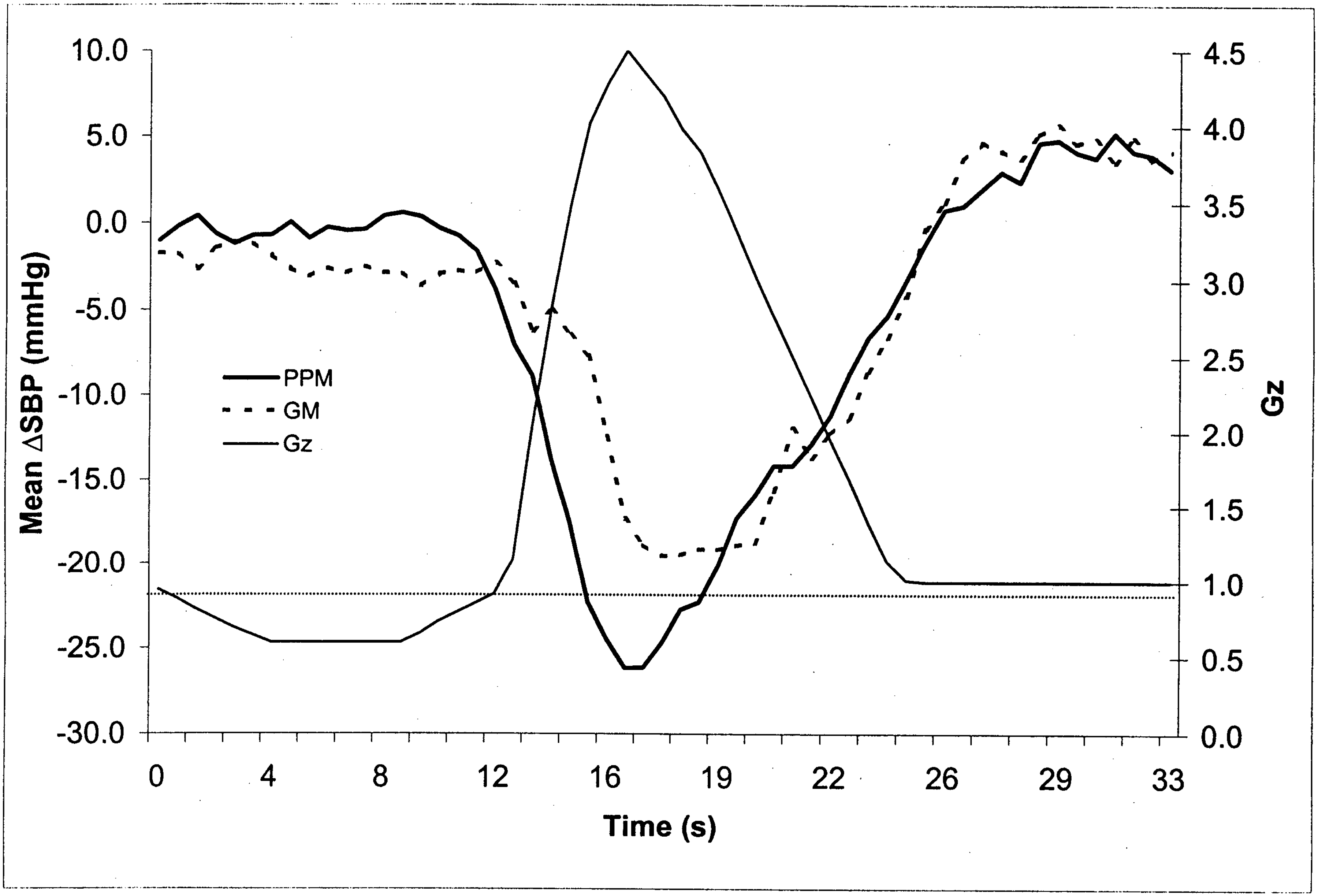
980
1080
1180
1280
1380
1480
1580
1680
1780
Time (s)

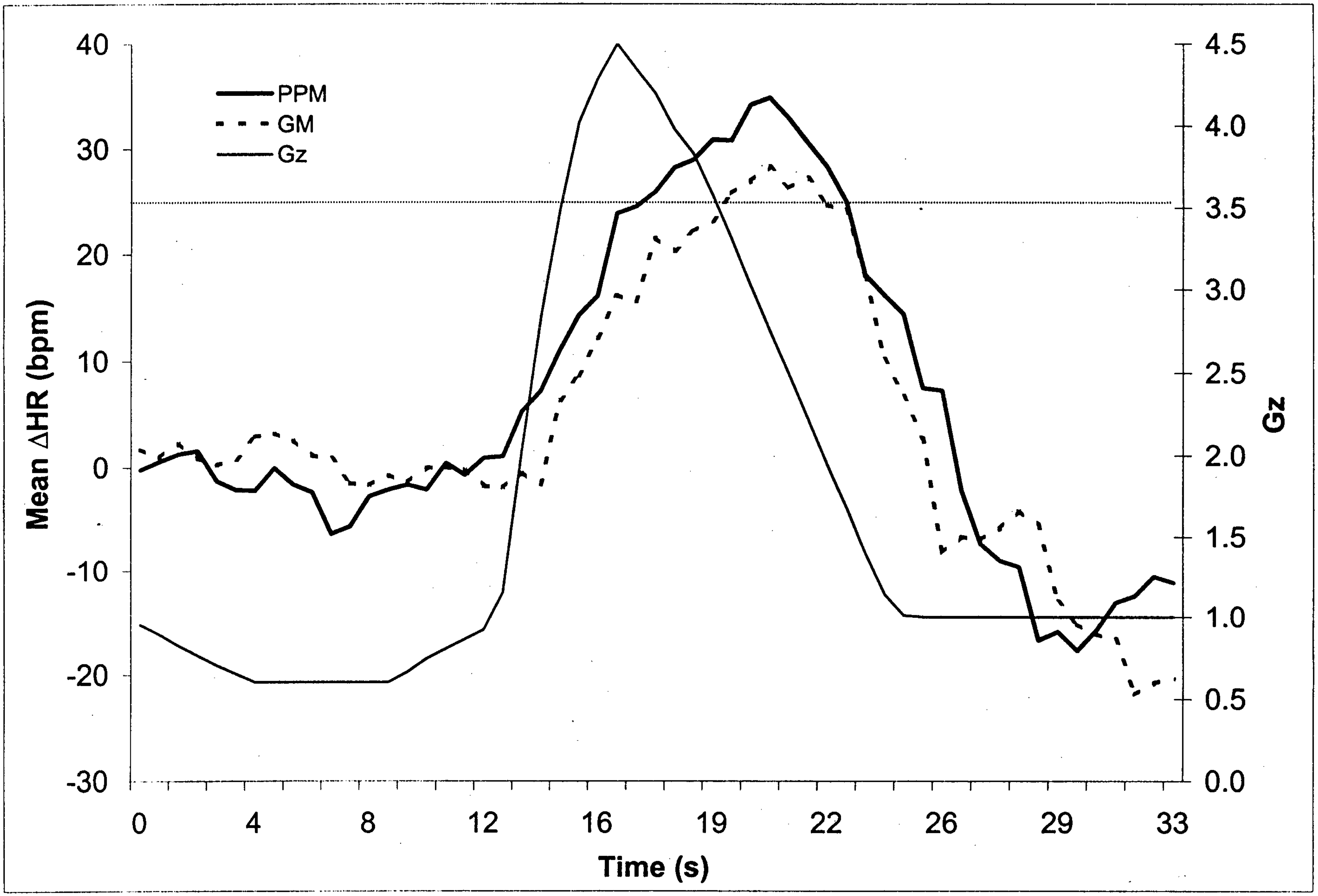
4

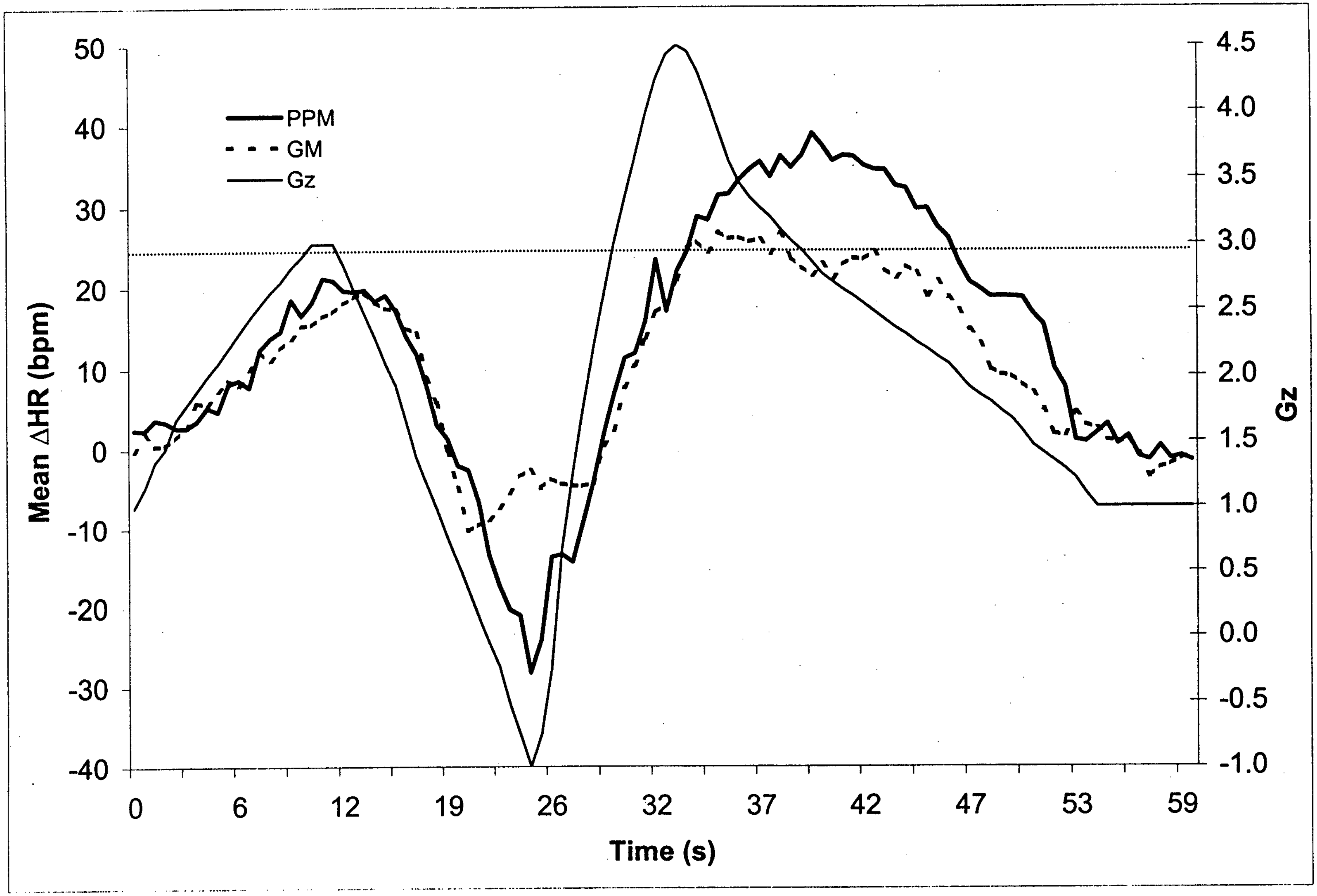


Gz
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
GOR1
ROR1
PO
L8
LHR
ROR2
LHG
ROR3
RLC
LOOP
HH
GOR2
0
2
3
5
7
8
10
12
13
15
17
18
20
22
23
25
Time (min)

5


10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
-30.0
Mean ΔSBP (mmHg)
PPM
GM
Gz
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Gz
0
4
8
12
16
19
22
26
29
33
Time (s)


PPM
GM
Gz
Mean ΔHR (bpm)
Gz
Time (s)
40
30
20
10
0
-10
-20
-30
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
4
8
12
16
19
22
26
29
33


PPM
GM
Gz
Mean ΔHR (bpm)
Time (s)
Gz
50
40
30
20
10
0
-10
-20
-30
-40
0
6
12
19
26
32
37
42
47
53
59
4.5
4.0
3.5
3.0
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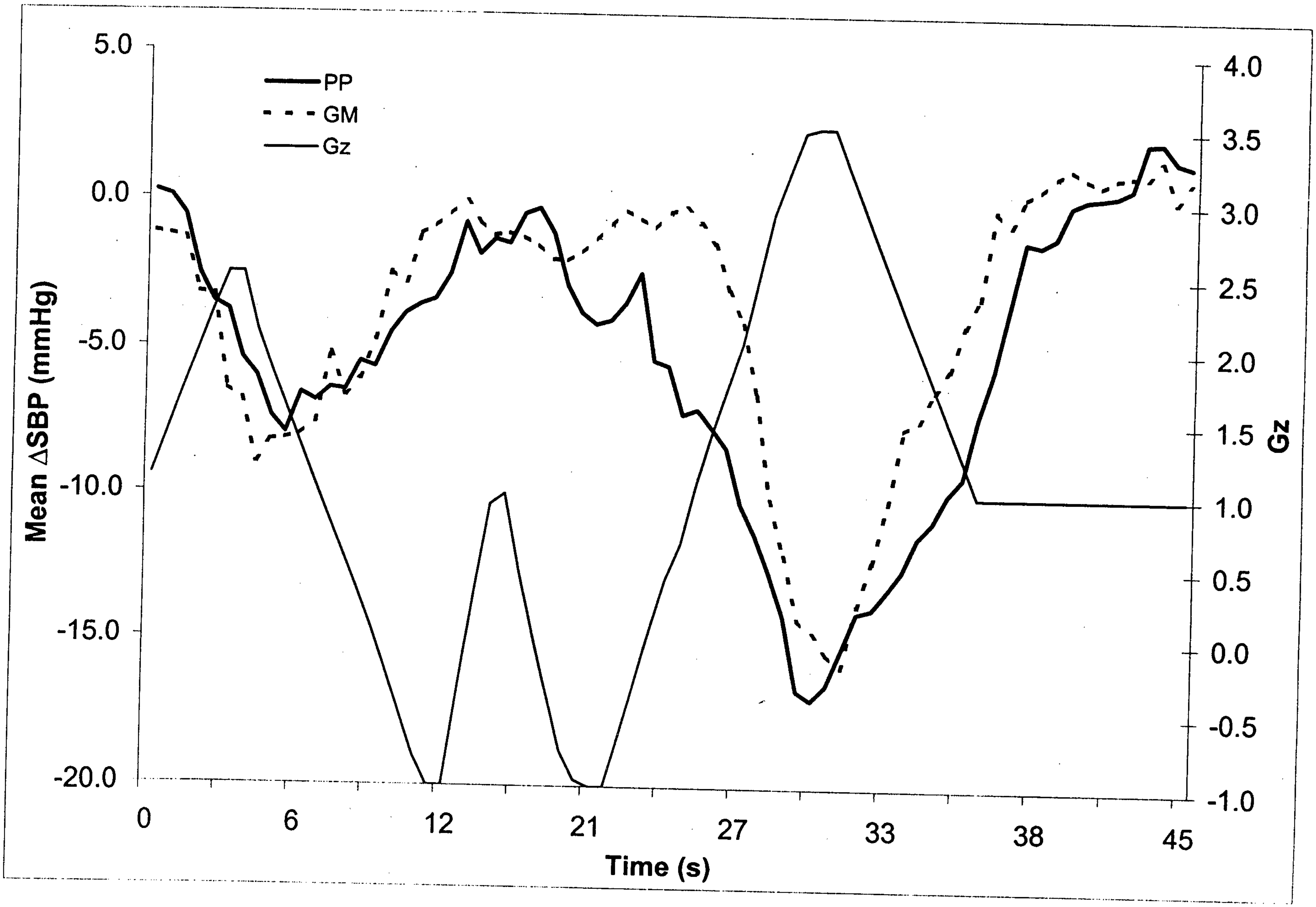
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0



PP
GM
Gz
Mean ΔSBP (mmHg)
5.0
0.0
-5.0
-10.0
-15.0
-20.0
Gz
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
0
6
12
21
27
33
38
45
Time (s)

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14. ABSTRACT

The risk to helicopter aircrew of acceleration stress was assessed by investigating the human physiologic response to transitions from -1 Gz (push) to +4.5 Gz (pull) loads. Nine volunteers participated in a study conducted at the Veridian Operations Centrifuge Facility in Warminster, PA. A 1-hr mission scenario consisting of nine helicopter maneuvers, based on in-flight G measurements (push-pull mission, PPM), simulated both current (CM: -0.2 to +3.5 Gz) and projected future platform capabilities (FM: -1 to +4.5 Gz). Measurements included blood pressure, heart rate (HR), loss of vision, and subjective fatigue. Visual decrements were minimal during CM while muscular tensing was required to avoid blackout during FM. Light loss typically occurred during the transition from -Gz to +Gz. Within the scope of these tests, subjects tolerated the range of Gz-stresses associated with current USN rotary wing platforms. When subjected to FM G-loads (typical of current USA platforms), cardiovascular stress significantly increased, Gz tolerance dropped as much as 1.2 G, and HR increased as much as 67 bpm. Cardiovascular changes were significantly greater during FM PPM relative to GM. Four subjects reported Almost-Loss of Consciousness symptoms during FM. While G-stress experienced by aircrew generated by current helicopters does not appear to present a high risk, G awareness training is recommended to reduce risks to aircrew exposed to G-loads generated by more aggressive helicopters. Future studies are required to determine the impact of longer mission times and dehydration.

15. SUBJECT TERMS

helicopter, G-tolerance, cardiovascular, A-LOC, flight simulation

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